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HELITRAK:

A helicopter-tracking receiver system for television outside broadcast links

C. Gandy, B.Sc.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

BBC RD 1992/5

HELITRAK: A HELICOPTER-TRACKING RECEIVER SYSTEM FOR TELEVISION OUTSIDE BROADCAST LINKS

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Summary

Helicopters are used by BBC Television for certain live outside broadcasts which require an elevated platform for a camera or for a radio-link mid-point repeater. Video signals are communicated from the helicopter to the ground using microwave radio links, and the signals are received by a narrow-beamwidth dish antenna which must be kept pointing accurately towards the aircraft. In the past, this receiving antenna has always been pointed manually, but in some circumstances the performance of the radio links can be limited by the ability of an operator to keep the antenna on track.

Such a limitation can be avoided by using an automatic tracking system; this Report describes the approach taken by Research Department to develop the 'HELITRAK' tracking receiver system. Unlike some of the proprietary counterparts, this is a set of equipment which facilitates automatic tracking when applied to an existing radio-link receiver. It is specially tailored to the requirements of a video transmission system and needs only one conventionally transmitted radio-link signal. It has the potential to increase the reliability and the maximum range of helicopter links, and to improve operational efficiency.

The text covers the development of the tracking system, detailing the operational requirements and the design options. The system uses a novel method of tracking by detecting the direction of incoming RF signals, using higher-order mode synthesis in the antenna feed. Operational experience (from use in live outside broadcasts) and system limitations are noted, and areas for further improvements are identified.

Index terms: *Tracking systems; TV links; radio-cameras; SHF; TV broadcasting; antenna-RX; field tests*

Issued under the Authority of

Ian Childs

Head of Research Department

Research Department, Engineering Division
BRITISH BROADCASTING CORPORATION

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1. Introduction 1

2. Background 2
   - 2.1 Radio frequencies 2
   - 2.2 The transmitter 2
   - 2.3 The receiver 3
   - 2.4 Manual tracking 3

3. Requirements of the Tracking System 4

4. Choice of the Tracking Scheme 4
   - 4.1 Absolute location 4
   - 4.2 Bearing determination 4
   - 4.3 RF signal sensing 5
     - 4.3.1 Tracking by higher-order mode synthesis 6

5. Description of the Components in the System 8
   - 5.1 The antenna 8
   - 5.2 The receiver 9
   - 5.3 The positioner and servo-amplifier 9
   - 5.4 The processor 10
     - 5.4.1 The microcomputer monitor 11

6. Development of the Components 12
   - 6.1 The antenna 12
   - 6.2 The receiver 12
   - 6.3 The positioner 12
   - 6.4 The processor 12

7. Outside Broadcast Use of the HELITRAK System 12
   - 7.1 Future improvements 13

8. Conclusions 14

9. Acknowledgements 14

10. References 14

Appendix: Link Budget for a Typical Air-to-ground Link 15

(T-13)

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HELITRAK: A HELICOPTER-TRACKING RECEIVER SYSTEM FOR TELEVISION OUTSIDE BROADCAST LINKS

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1. INTRODUCTION

Certain live outside broadcast (OB) operations require an elevated platform for a television camera, or for a radio-link mid-point repeater which relays signals from a radio-camera[1] on the ground. When the action being covered is spread over a large area, or when camera shots from high altitude are more appropriate to the presentation of the programme, in BBC Television operations, the platform is often provided by a helicopter. An example of the aerial camera* application is shown in Fig. 1.

Video signals are communicated from the helicopter to the ground using one or more microwave radio links. Setting up a number of receiving stations on the ground can be costly, so usually the signals are received at only one site; the length of the propagation path (the range) can vary from less than 1 km to 80 km, or more. An omnidirectional transmitting antenna is used, to make the performance of the links independent of the orientation of the aircraft, but this has little directivity gain. The available transmitter power is limited, so the only way to cater for long range operation is to use a high-gain antenna to receive the signals on the ground.

Such an antenna has a narrow beamwidth, so it must be kept pointing accurately towards the helicopter. In the past this has always been accomplished manually, by a combination of visual alignment, watching a meter (which displays the strength of one of the received signals), and watching a television monitor (which displays one of the received television signals after demodulation). When the aircraft is moving, this task demands a continuous high level of concentration, sometimes through adverse weather conditions. In some circumstances, the ability of an operator to keep the receiving antenna on track, limits the performance of the radio links severely. Poor

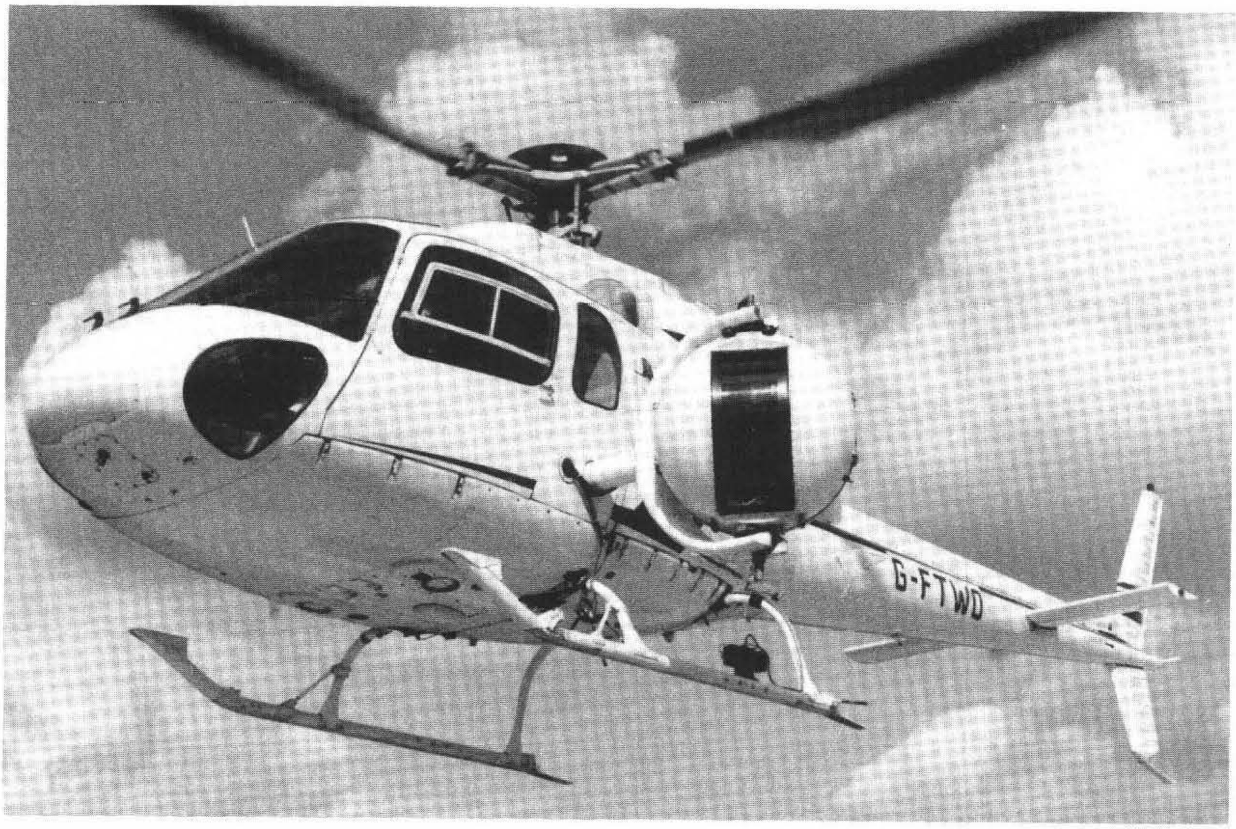

Fig. 1 - A helicopter equipped for aerial camera operations.

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* In the BBC, aerial camera operations are referred to as 'Helitele', which was the name of a former independent company which provided facilities for such operations. These facilities have been taken on by the BBC.

visibility, the helicopter being beyond visual range, or several flying in the same area, are circumstances which produce this problem.

The need for this manual operation can be avoided by using an automatic tracking system. This has the potential to increase the reliability and maximum range of air-to-ground links, and operational efficiency can be improved if it does not require the full-time attention of an operator. Recognising this, efforts have been made in the BBC to procure a suitable tracking receiver system. Several proprietary systems have been investigated by Television Outside Broadcasts (Tel. OBs) and Transmission Engineering Department. Most of these have either offered inadequate tracking performance, especially at short range, or their introduction would have demanded extensive re-equipping, because they are supplied as 'autonomous' systems which cannot readily be interfaced with existing RF equipment.

What was really needed, was a means to adapt an existing radio-link receiver to facilitate automatic tracking, which comprised as small a number of additional items as possible. Such a system was not available as a manufactured item, so the requirement was presented to Research Department. With the aims of satisfying this, and several technical requirements, a project was set up which led to the development of the HELITRAK* system, which will be described in this Report.

2. BACKGROUND

2.1 Radio frequencies

The radio links carry conventional 625-line PAL television signals using FM, and each occupies an RF bandwidth of up to 20 MHz. Associated audio signals are carried by FM subcarriers added to the baseband video signals.

Frequency assignments for such links are available in bands at about 2.5 GHz, 3.5 GHz, 5.5 GHz, 7 GHz, 12 GHz and 48 GHz. Most of these bands are planned with a number of discrete channels, each 20 MHz wide. Six channels are available to the BBC in the 2.5 GHz band, but of these, only three can be used with an airborne transmitter. Two channels are also available for airborne transmission in each of the 5.5 GHz and 7 GHz bands.

The higher frequency bands may be used for helicopter links in the future, but, at the present time, proprietary radio-link equipment for the 2.5 GHz band offers the most favourable combination of high transmitter power and low receiver noise figure. This band also offers the lowest propagation losses during rainfall conditions. Therefore, only the 2.5 GHz band is used by the BBC for helicopter links. When a mid-point repeater (actually a transponder) is established in the aircraft, different channels in the 2.5 GHz band are used for the incoming and outgoing links. An incoming link poses relatively few problems because it usually has short range (i.e. the helicopter is usually kept directly above the radio-camera), so this will not be discussed in detail here.

2.2 The transmitter

Special equipment-mounting assemblies have been constructed by Tel. OBs for temporary installation in hired helicopters, to accommodate one or more transmitters, and receivers, if needed, for mid-point operations. It is not exceptional for a helicopter to carry a two-channel mid-point transponder *and* the transmitter for an aerial camera; in this case, all three transmitter signals are multiplexed into the same transmitting antenna. A typical helicopter rig is shown in Fig. 2, comprising receivers, transmitters and multiplexing filters.

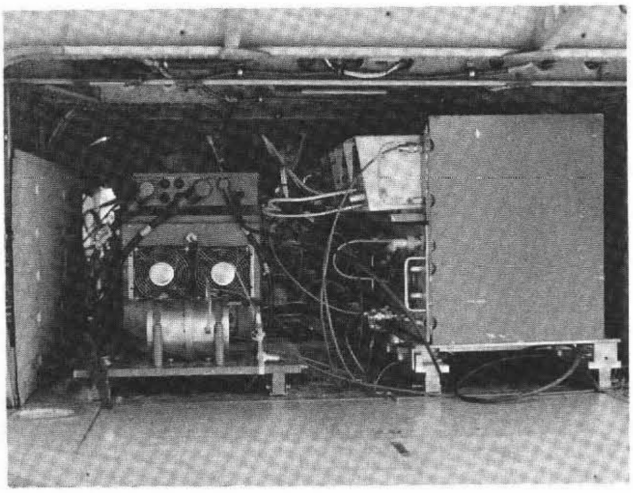

Fig. 2 - Radio-link equipment mounted inside a helicopter.

The transmitting antenna is either a dipole or a Franklin (collinear) array[2] slung beneath the fuselage of the helicopter on an electric actuator. Both types of antenna are linearly polarised, operated as vertically polarised, and have omnidirectional radiation patterns in the azimuth plane. The actuator is often attached to one of the landing skids, and is used to deploy the antenna vertically below the skid after take-off, and to stow it horizontally alongside the skid before landing.

Both types of antenna exhibit nulls along their axes. The upwards null helps to suppress multipath propagation from the rotor blades, but the downwards null can cause a reduction of the received signal strength if the aircraft is banked steeply. The Franklin array has a more restricted pattern in the vertical plane, providing some 3 dB gain relative to a dipole; but additional nulls in this pattern, some 11° above and below the peak response in the horizontal plane, can also cause signal loss during banking manoeuvres. Essentially, these antennas are intended to be used with a helicopter in level flight.

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* 'HELITRAK' is a registered trade mark, and the BBC has rights to its use in relation to this 'ground based' tracking receiver system.

2.3 The receiver

The signal is received by an antenna located on the rooftop of a suitable building or on the roof of an OB vehicle. The receiving antenna is usually a 1.1 m diameter dish reflector mounted on a pan-and-tilt head which sits on a tripod. This is fitted with an open-ended circular waveguide feed (sometimes known as an OMT feed, because it has a similar form of construction to a waveguide Orthogonal-Mode Transducer, with probes feeding coaxial cables). This combination is directed manually, or 'panned' towards the helicopter. The antenna is connected to a conventional 2.5 GHz radio-link receiver, and the receiver's AGC meter can be used to judge optimum pointing. Additionally, a small television monitor is sometimes attached to the pan-and-tilt head, displaying the demodulated television signal; this is useful for estimating the performance of the link.

At 2.5 GHz, a 1.1 m dish antenna has a beamwidth of only 8°, so a fair degree of pointing precision is required. Sometimes two, or more, independent receivers are used to provide diversity reception. In this case, one of the receivers may use a 0.6 m dish which halves the precision required, although, generally, it yields 6 dB less signal-to-noise (S/N) ratio. A typical arrangement of manual receivers on a rooftop is shown in Fig. 3. The link budget for a typical air-to-ground link is presented in the Appendix.

2.4 Manual tracking

When the helicopter reaches the limit of visual range, the AGC meter and the television monitor become the only sources of tracking information. Manual operation can still be effective because at long range the apparent rate of angular motion of the helicopter is small. However, the signal from the aircraft can suffer momentary fading owing to a number of causes, and this can mislead the operator into making unnecessary antenna movements. Typical causes are:

(a) Multipath propagation due to reflections from the ground and buildings.

(b) Fading caused by banking (involving the vertical radiation pattern of the transmitting antenna).

(c) Path blocking when the aircraft flies behind a building.

The problem is that the AGC meter and the television monitor are both 'unipolar'; that is, they

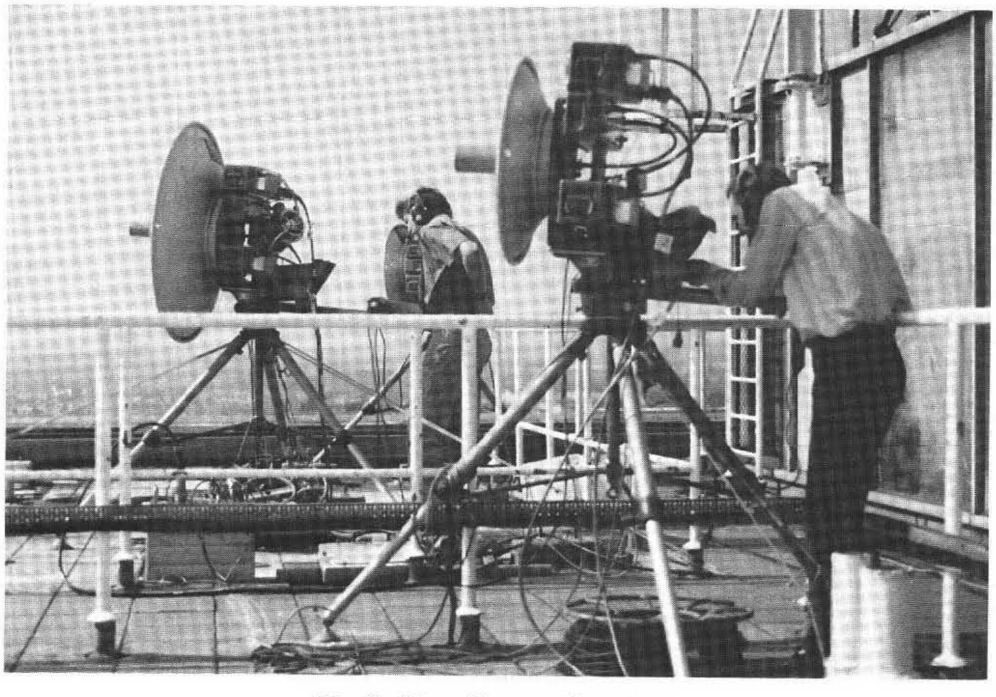

Fig. 3 - Manually panned receivers.

indicate increased or decreased signal strength but, by themselves, give no information about which way the antenna should be panned to improve matters. The only way directional information can be gained is by moving the antenna in small angular steps; perhaps, initially, in the wrong direction. The strength of the received signal can then be optimised, and if the steps are sufficiently small, the changes in the S/N ratio of the demodulated television signal may be imperceptible. Unfortunately, one 'false move' can easily degrade the S/N ratio significantly, especially when most of the link margin has been used up by the long range, or by fading.

Thus, at long range, the manual tracking process is similar to the 'step track' principle, which is often applied to satellite earth stations, and is usually implemented using a computer. However, when the aircraft can be seen and the operator is aware of the direction in which it is flying, the process is bipolar and is more akin to the 'monopulse' tracking principle used in earth stations and in radar.

3. REQUIREMENTS OF THE TRACKING SYSTEM

To overcome the shortcomings of the manually-panned antenna, an automatically-tracking receiver system was required, and to avoid the expense of re-equipping for another frequency band, operation at 2.5 GHz was desirable. To save the cost of completely re-equipping for helicopter operations, it was decided that, wherever possible, components of existing radio-link equipment would be re-used. These components are standardised within the BBC.

It was hoped that neither additional equipment nor additional antennas would need to be carried by the aircraft, where space inside the fuselage and sites for mounting additional antennas were already minimal. To avoid the need for additional radio-frequency spectrum, it was desirable that the system should use only an existing 2.5 GHz radio-link signal radiated from the helicopter. Also, the system was required to work without leaving visible 'artifacts' in the received video signal.

The system was required to track a moving helicopter at a maximum apparent angular rate of about 3 degrees per second. This is derived from a minimum ground-range of 800 m (0.5 mile), a minimum altitude of 152 m (500 feet) and a maximum operational air-speed of 148 km/hr (80 knots). The maximum altitude was specified as 610 m (2000 feet), and the maximum range length about 80 km (50 miles), although this should be limited by the FM radio-link receiver reaching threshold conditions, not by failure of the tracking system (see the Appendix). The range of elevation angles is then 0 to 37 degrees, and in the azimuth plane the full 360 degrees coverage is required.

With these requirements in mind, and other considerations such as complexity and cost, a suitable tracking scheme was chosen.

4. CHOICE OF THE TRACKING SCHEME

Because of the limited beamwidth of the receiving antenna, tracking is required in two planes; typically, azimuth and elevation. The need for tracking in the elevation plane could be overcome by using a special antenna with a tailored radiation pattern in the vertical plane (actually following a cosecant-squared law); this is not uncommon in airfield radar systems. However, to uphold the antenna gain, and therefore the maximum range, this antenna would need to be much larger than the standard 1.1 m dish.

Fundamentally, there are two ways to make an antenna track a moving target: indirectly, by absolute location; and directly, by bearing determination.

4.1 Absolute location

If the locations of the target and the tracking station are known, in all three dimensions, trigonometry gives the required antenna pointing angles. This method can be implemented using an airborne navigation system, relaying to the ground the coordinates of the helicopter.

Several radio-navigation systems are now available, including the terrestrial LORAN and Decca Navigator systems, and the satellite 'Navstar' Global Positioning System (GPS). Systems based on a network of terrestrial transmitters often suffer from discontinuous coverage, and would require the addition of altimeter data to give a full set of coordinates. The GPS is believed to have reached the point where near-continuous coverage of the earth is provided for most of the time. The availability of low cost GPS receivers made this approach worthy of consideration.

The use of any navigation system would, however, require additional spectrum to relay positional information back to the receiving station, and additional airborne equipment, including an antenna.

4.2 Bearing determination

This method provides the pointing angles directly. It can be implemented using primary or secondary radar (the latter using a radar transponder in the aircraft), by optical tracking, or using a system which tracks an RF signal transmitted from the helicopter.

Radar was ruled out, because it would have required much additional ground-based equipment and additional RF spectrum.

Optical tracking systems are available, and have the advantage that they need no RF spectrum. However, the maximum range of a passive system, which relies on sunlight to illuminate the target, is invariably less than 80 km; it can be limited further by weather conditions, and tracking can be upset if a second aircraft flies in the same area. A powered system, similar to primary radar but transmitting with a laser, would be potentially hazardous if, indeed, one could be built for that maximum range.

4.3 RF signal sensing

The most suitable and simple approach appeared to be passive RF-signal sensing, using either an existing radio-link signal or a separate 'pilot' signal transmitted from the aircraft. The use of a pilot signal was attractive because in the receiving equipment this could be processed and chopped as necessary without disrupting the received television signals. However, it would demand additional spectrum, some additional airborne equipment, and maybe an additional ground receiver. Therefore, the choice was narrowed down to an RF sensing scheme using only an existing radio-link signal.

Compared to primary radar and optical tracking, this method has the obvious disadvantage that tracking can only function when the radio-link transmitter is switched on and a clear, unobstructed path is available between the helicopter and the ground receiver. However, these conditions are prerequisite for communicating television signals, so, provided that the system did not take unduly long to re-acquire 'track' after a transient signal loss, the RF sensing method was thought to be equally effective. This method was also considered to be the least expensive option.

There are several ways in which an RF-signal sensing scheme can be implemented using a reflector antenna, including:

(a) **Step track**; where the antenna is moved, bodily, in small steps, changing the beam direction repeatedly. The result of each step, judged by whether the received signal level increased or decreased, is used to determine the direction of the next step. For this application the process would be carried out, perhaps sequentially, for two orthogonal planes of motion.

(b) **Conical scan**; where the antenna beam is moved continuously around the boresight direction (i.e. the normal to the aperture plane of the reflector), describing a cone. This is usually accomplished by moving only part of the antenna (e.g. the feed), and provides azimuth and elevation information sequentially during each scan.

(c) **Sequential lobe scanning**; similar to conical scan but using a number of discrete beam directions (i.e. lobes) about the boresight direction (e.g. up, down, right and left), giving information for two planes sequentially during each scan.

(d) **Monopulse**; where for each plane of interest the antenna is fed in a way which endows it with symmetrical 'sum', and antisymmetric 'difference', radiation patterns. For each plane, the solution of simultaneous equations using the 'sum' and 'difference' signal voltages gives a bipolar signal representing the direction and degree of the angular tracking error. These signals can be produced simultaneously and instantaneously.

Whatever the sensing scheme, the antenna would be mounted on a dual-axis positioner and the angular error information would be processed to give the appropriate motor drive signals. From the outset, it was hoped that the only moving parts would be in the positioner.

The advantage of the first three systems over the manual operation described earlier (to which they bear some resemblance), is that these processes are continuous; so, at least in principle, errors are not allowed to accumulate. The mean direction of the antenna beam is kept close to the ideal, so the small changes of direction should introduce only small variations in the S/N ratio of the received signal.

The speed of a step track system would be limited by the ratio of the inertia of the antenna assembly to the available torque of the positioner motors. In this application, for continuous operation, rather large motors and very robust mechanical components would be required.

Conical scan, with vertical polarisation, would require a nutating feed*; a complicated arrangement of bearings and flexible or rotary joints.

* A nutating feed progresses cyclically around a circular path, surrounding the focus of the reflector, but with its orientation (and hence its polarisation) held constant.

The monopulse approach requires a complex feed system, because the sum and difference antenna responses are usually formed by processing signals at the incoming radio frequency. Sum and difference RF signals are then passed to a dedicated *dual-channel* tracking receiver, which converts the signals to an intermediate frequency (IF) in phase synchronism, and then applies the simultaneous equations. A monopulse feed for a reflector antenna consists of either: an array of similar elements (e.g. horns or dipole/reflector combinations) with individual output ports; or, a single element (such as a horn) which can respond to several different modes of excitation, and can provide separable outputs (e.g. by the extraction of higher-order waveguide modes). Monopulse can provide great angular precision and speed of operation, in excess of the requirements of this application, and is the most costly option.

The sequential lobe scanning approach has been used in some proprietary helicopter tracking systems which employ a multiple feed. An example is the use of a central horn at the focus of the reflector, surrounded by four peripheral horns. The radio-link signal is received conventionally, using the central horn, and a separate tracking receiver is connected in commutation to each of the peripheral horns to derive the tracking information. The peripheral horns, offset from the focus, each give a radiation pattern which is angularly offset from the central, boresight direction. With four peripheral horns, the offsets can be up, down, right and left of the boresight. This method provides some simplification over the monopulse approach but it still needs a dedicated SHF tracking receiver.

The most favoured approach was sequential lobe scanning using a new type of feed which allows high-speed electronic control of the beam direction, and tracking without a second, dedicated, receiver.

4.3.1 Tracking by higher-order mode synthesis

This new approach^3 involves no moving parts within the antenna and very simple electronics. It can provide tracking information at a very high update rate, and a single receiver can be used for tracking as well as for communication.

In this application a central horn feed is used, surrounded by four peripheral open-ended waveguides (i.e. horns with no flare angle). The waveguides are coupled parasitically to the horn by the proximity of their apertures, and only the horn is connected to the receiver. Each waveguide is terminated by a short-circuit plug, and contains a shunt PIN-diode switch some distance between this and its aperture. This arrangement is illustrated in Fig. 4. The electrical length of each of these waveguide 'stubs' is thus determined by the on/off state of its PIN switch, so the relative phase of the signal re-radiated by its aperture can be controlled electronically, and independently.

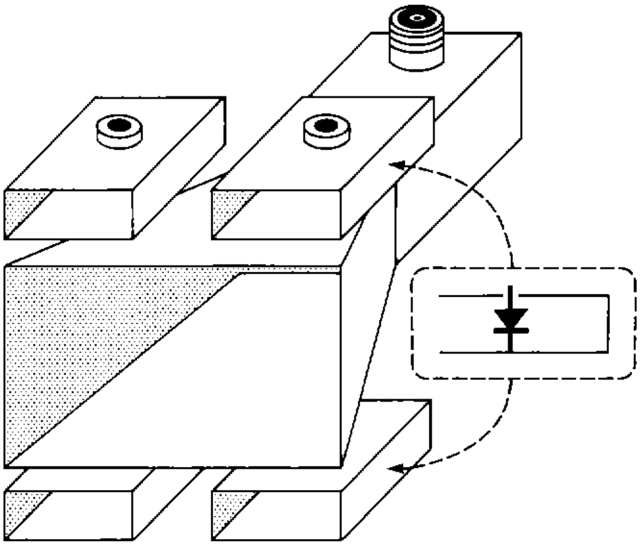

Fig. 4 - General arrangement of the higher-order mode synthesis feed.

Some portion of each re-radiated signal is coupled into the central horn, so by appropriate choices of the electrical lengths it is possible to synthesize piece-wise a phase slope in the response of the feed across its overall aperture. The fields in the focal plane of a symmetrical parabolic reflector have a symmetrical distribution of phase when receiving a signal from the boresight direction; but when the direction of arrival is offset from the boresight, this introduces anti-symmetry, or a phase slope. In this case, the feed is mounted in, or close to, the focal plane, so the synthesized phase slope has the effect of offsetting the direction of maximum response (i.e. the antenna beam) away from the boresight. The action of introducing antisymmetric phase-shifted elements into the focal field of the reflector, is analogous to the introduction of suitably phased higher-order modes into a waveguide horn feed. The effect is synthesised in this case, but the end result is the same.

With a symmetrical arrangement of four peripheral waveguides, appropriate combinations of the PIN switch states allow the beam to be offset in four discrete directions (e.g. up, down, right and left of the boresight), ideally by the same, small angle in each case. This angle depends on the relative magnitudes of the responses to fields exciting the central horn and the peripheral waveguides, so it is governed by the degree of coupling, and hence the physical arrangement of the apertures. With all four switches set to the same state, symmetry is restored and the beam reverts to the boresight direction.

By commutating the control signals to the PIN switches (which forms these signals into pulses), the beam direction can be commutated for the required sequential lobe scan. This is illustrated in Fig. 5, where the cross-section of the antenna beam is considered as circular. If the transmitting helicopter is away from the boresight direction, then signals of different strengths will be received during the different stages of the scanning sequence.

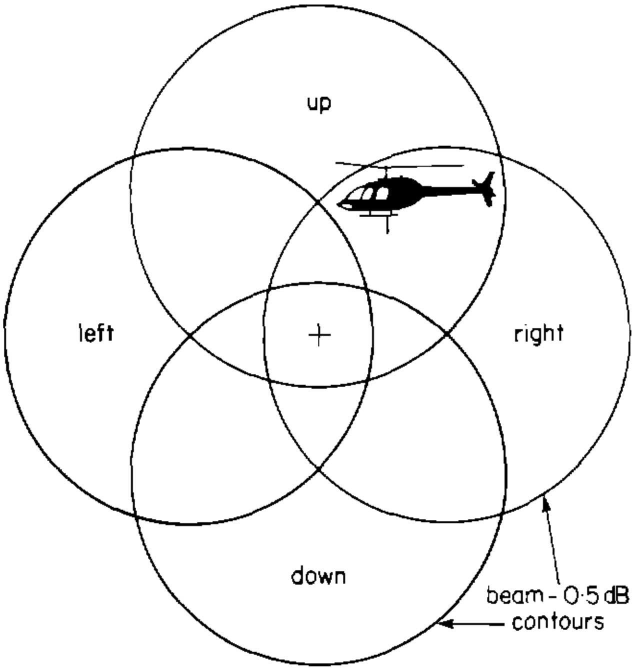

Fig. 5 - The sequential lobe scan.

By measuring the strength of the received signal at instants within the PIN switch pulses, independent information can be gained about the degrees of tracking error for the azimuth and elevation planes, as shown in Fig. 6. Taking the difference between two voltages representing the signal strengths for the 'up' and 'down', or 'left' and 'right' beam offsets, an 'error' signal is derived for each plane. The magnitude of each error signal depends on the radiation patterns of the corresponding pair of offset beams, their angles of offset, and the angular displacement of the antenna's boresight direction from the transmitting helicopter, as illustrated in Fig. 7.

The signal strength is measured using a logarithmic amplifier/detector, which outputs a voltage proportional to the relative signal strength in decibels, and this has two beneficial effects. Firstly, it gives an approximately linear relationship between the magnitudes of the error signals and the angular displacements they represent, giving 'tracking slopes' as illustrated in Fig. 8. Secondly, it makes the magnitudes of the error signals essentially independent of the mean signal strength, so they are not influenced by changes of the range, transmitter power or receiver gain, occurring at rates much less than the rate of commutation.

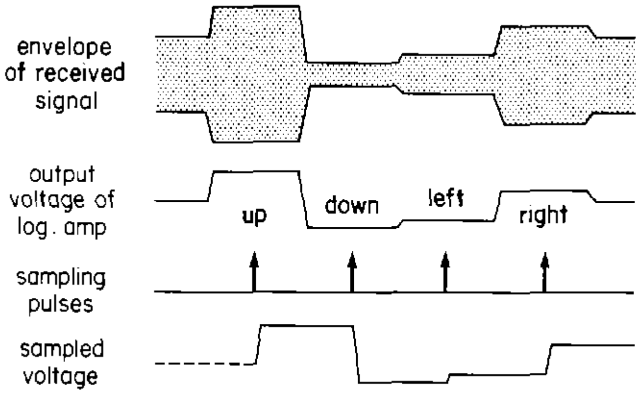

Fig. 6 - Sampling the strength of the received signal to obtain tracking information.

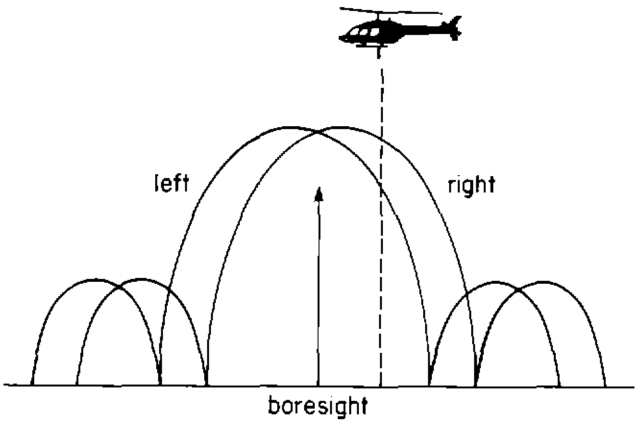

Fig. 7 - Radiation patterns for one pair of offset beams.

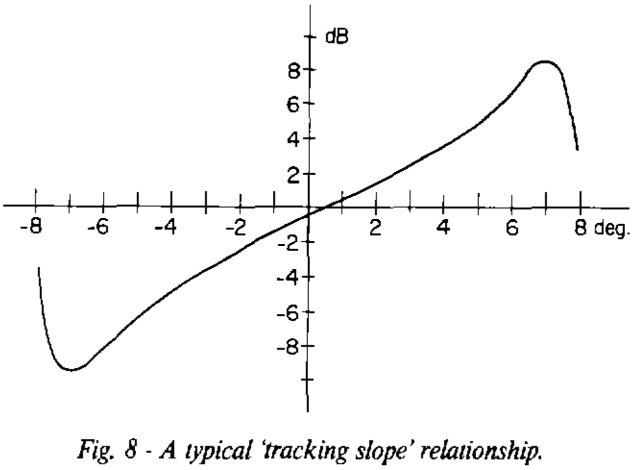

Fig. 8 - A typical 'tracking slope' relationship.

The error signals are made quasi-continuous by applying them to sample-and-hold circuits followed by low-pass filters; then they are amplified and fed in the appropriate senses to the positioner motors. Thus, an independent pair of position control loops is formed, and these apply negative feedback to reduce the angular tracking errors. As the antenna is steered to line up its boresight direction with the helicopter, the errors approach zero and the same signal level is received throughout the scanning sequence.

The key to using only one receiver is to limit the degrees of offset to only about one tenth of the beamwidth (about 0.8° in this case), so the degree of AM imposed on the received signal is very small when the tracking errors are small (less than 1 dB per degree of error). In steady-state conditions, within the bounds of stability and S/N ratio, the angular tracking errors can then be made as small as desired by increasing the control loop gains.

Obviously, the S/N ratio of the received signal decreases as the range length increases and the mean signal level decreases. The radio-link FM demodulator would be expected to fail when the carrier-to-noise ratio of the received signal fell to about 11 dB in the 30 MHz receiver noise-bandwidth. However, the control loop bandwidths can be made very much smaller. Typically, 5 Hz is sufficient to follow all expected helicopter manoeuvres, so at maximum range the S/N ratio of the AM envelope signal passed to the tracking system can still be large.

The kind of wideband FM demodulator used in the radio-link receiver would have some response to AM, but it is preceded by an amplitude limiter. This is effective in removing traces of spurious AM caused by multipath propagation from the rotor blades, especially during banking manoeuvres when the path to the ground receiver is not on the peak of the transmitting antenna's response. Therefore, in most circumstances, the small degree of additional AM introduced by the sequential lobe scanning will cause no disruption to the received video signal. However, to prevent the appearance of visible artifacts in exceptional circumstances when large errors exist, such as during re-acquisition of track after a transient outage, it is desirable to change the beam direction only during the television field-blanking intervals. Any remaining artifacts can then be removed by simple video processing.

With a radio frequency of 2.5 GHz, the rate at which the beam direction can be changed is essentially limited only by the speed of the PIN switches, and advantage can be gained by performing a complete up-down-right-left sequence during each field-blanking interval. This is because the cycles of AM from the rotor blades can have a similar period to the 20 ms television field period. If the scanning sequence was spread over several fields the tracking performance could be upset by a beat between the rates of the intentional AM, from the sequential scan, and the spurious AM. Furthermore, the choice of a sequence with the differential pairs adjacent (i.e. 'up' followed by 'down'; 'left' followed by 'right') ensures that any slope due to the spurious AM will have the least effect. During active television fields, when picture material is transmitted, the beam can be returned to the boresight direction to make the greatest use of the available antenna gain (on the basis that the tracking is accurate).

This approach was chosen as the most effective way to fulfil the requirements described in Section 3.

The application of this approach to time-discontinuous signals, especially television signals, is novel and has been patented[4].

5. DESCRIPTION OF THE COMPONENTS IN THE SYSTEM

A block diagram of the complete tracking receiver system is shown in Fig. 9.

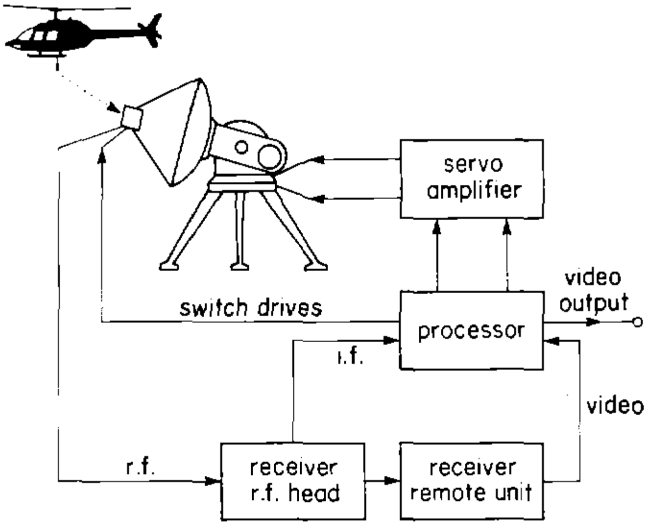

Fig. 9 - Block diagram of the tracking receiver system.

5.1 The antenna

The antenna assembly is shown in Fig. 10. The standard 1.1 m dish reflector is mounted on a motorised positioner and the higher-order mode synthesis feed is supported at its focus by four rigid struts, as shown in Fig. 11; the supporting hardware is designed for quick assembly. The central horn is terminated by a waveguide-to-coaxial transition, and a single low-loss coaxial cable connects this to the RF head unit of the radio-link receiver, which, to economise on positioner torque, is located nearby on the floor (or roof). A screened multi-way cable connects the PIN switches to a remote electronics package; the 'processor'.

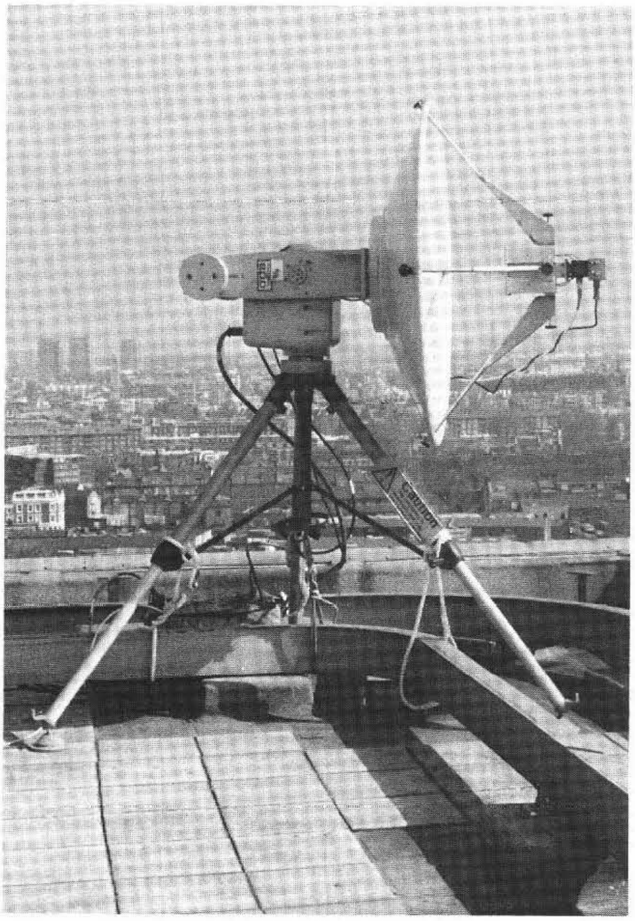

Fig. 10 - The antenna assembly.

5.2 The receiver

The receiver is basically of the standard type used extensively in the BBC. It comprises two sections, the RF head unit and the remote control unit, which are coupled by a single triaxial cable and can be located more than 50 m apart. The only modification which was necessary to accommodate the HELITRAK system was the inclusion of a 'linear' IF output port on the RF head unit, taken from a stage following the bandwidth-defining filter, but prior to the application of AGC and limiting. This simple modification has been applied to several existing receivers.

5.3 The positioner and servo-amplifier

The positioner is mounted on a standard radio-link tripod, and provides elevation-over-azimuth motion; it is shown in Fig. 12. It covers an elevation range of −3° to +90°, with respect to the horizontal, and an azimuth range of 390° (i.e. there is a 30° overlap sector). A screened multi-way cable connects the positioner motors to a remote servo-amplifier unit, shown in Fig. 13, which contains independent gain and power output stages for the two axes, providing the drive currents for the motors. This cable also carries position-indication signals from two potentiometers connected mechanically to the axes of motion; in the servo-amplifier unit, electrical 'end stops' are applied using these signals.

Another screened multi-way cable connects the servo-amplifier unit to the processor. The servo-amplifier unit can be located, with the receiver remote-control unit and the processor, some 50 m away from the antenna and positioner; indoors, or in a radio-link vehicle.

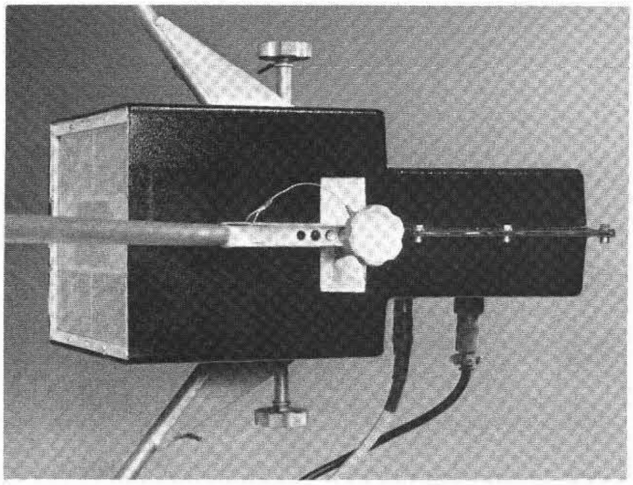

Fig. 11 - The antenna feed.

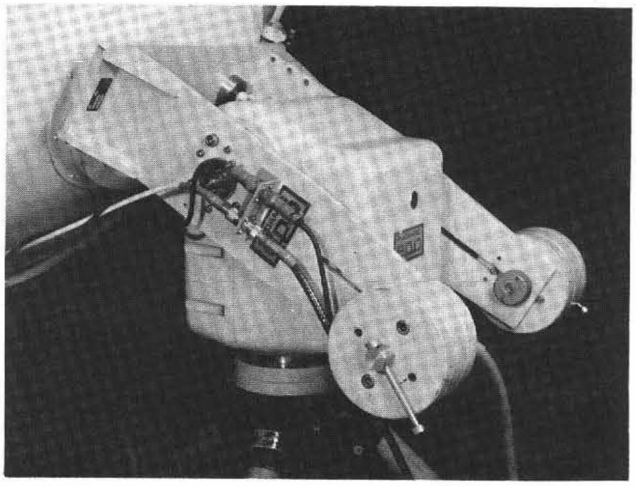

Fig. 12 - The motorised positioner.

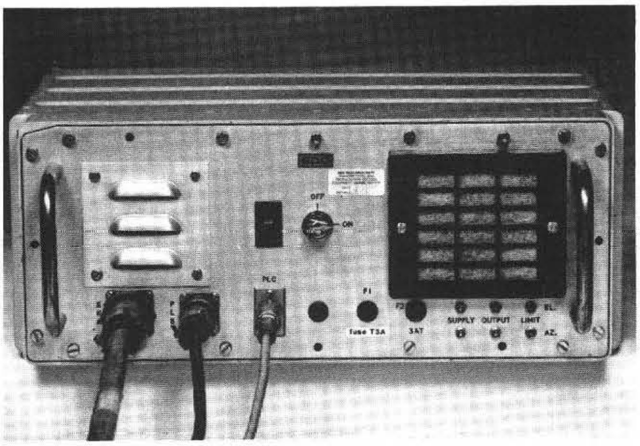

Fig. 13 - The servo-amplifier unit.

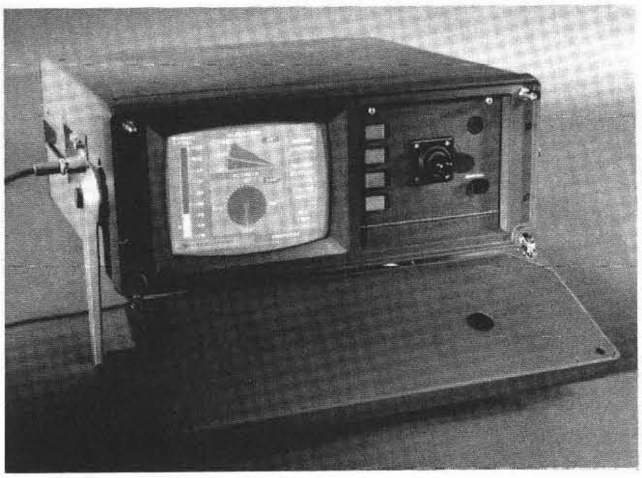

Fig. 14 - The processor.

5.4 The processor

The processor, shown in Fig. 14, contains the remainder of the circuitry which makes up the tracking system.

Fundamentally, there are two signal paths through the processor:

(a) **An ancillary path**; which takes in the demodulated video signal from the receiver remote control unit and outputs the PIN switch pulses to the feed.

(b) **The main, control and monitoring path**; which takes in the IF signal from the receiver RF head, and the position-indication signals from the positioner (via the servo-amplifier unit), and outputs analogue motor commands to the servo-amplifier. Much of the circuitry in this path is duplicated for the two axes of motion. Timing from the video signal is also used in this path.

During each television field-blanking interval, the antenna beam is offset to each of the four directions consecutively. Each offset lasts for the duration of two television lines, so a total of eight of the otherwise blank lines are used for tracking. During each active television field, the beam is returned to the boresight direction. The timing for this operation is derived from the syncs. of the received video signal. A 'flywheel' sync. separator is used for this, allowing the system to keep operating, even if the incoming signal is severely degraded or lost transiently. The relationship between the timings of the beam offsets and television syncs. is illustrated in Fig. 15 for the odd field; the

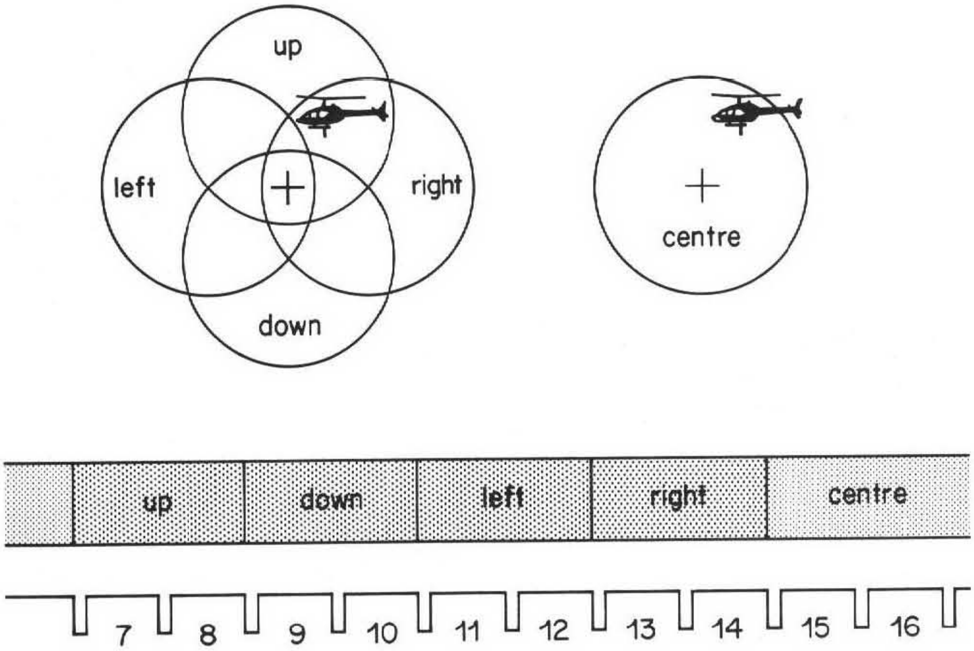

Fig. 15
Relationship between the timing of the beam offsets and television lines.

sequence in the even field is similar, with 313 added to the line numbers.

The 70 MHz 'linear' IF signal is input to the logarithmic amplifier/detector which detects the AM envelope of the received signal. Its output signal is sampled, separating the azimuth and elevation information to derive the two error signals. Under normal conditions the error signals are then sampled-and-held at television field rate, filtered and passed to the servo-amplifier, completing the control loops.

By suitable choices of the loop gains and loop filtering, these simple linear control loops can provide tracking for most expected conditions of constant position, constant velocity and constant acceleration. However, for initial acquisition of track, and to cater for transient outages, some non-linear assistance is provided by a microcomputer.

5.4.1 The microcomputer monitor

The microcomputer is based on the BBC Master Series 128 model, it provides a graphic display of the system's status and adds a degree of 'intelligence' to the operation of the system. When the system is tracking in normal conditions, the micro. takes no action within the feedback loops but merely reports on the system's status. However, if the signal is lost, or some other exceptional condition occurs, it can intervene and take control of the system, or it can provide manual (i.e. open loop) control to the operator; the choice is one of several programmable options.

The operating display is shown in Fig. 16, and this is used whilst tracking. Alternatively, an 'offset' display can be selected which shows the magnitudes of both tracking error signals simultaneously by the position of a small helicopter icon on a 'gun sight' background, as shown in Fig. 17.

If automatic acquisition is selected, the micro. steers the antenna, bodily, through a limited raster scan whilst logging signal levels, and, if a signal is detected, a step track process begins in order to optimise the antenna direction. When the error signals are sufficiently small in magnitude, the system changes over to sequential lobe scanning and the feedback loops are closed. However, if the signal is not found, the width and height of the raster scan are increased progressively. In this process, it is assumed that the wanted signal from the helicopter will be the only one which can appear in the passband of the receiver, which is generally true.

If automatic re-acquisition is selected, when an outage occurs which lasts for more than the pre-set time-out period, the system implements the same step track process to try to regain track. During the time-out period, the antenna is held at its previous direction, and if the signal re-appears, tracking resumes.

If the manual option is selected in either case, the micro. hands control over to the operator, making a joystick active for controlling the positioner directly.

All important parameter values are stored periodically in a battery-backed RAM. In the event of a brief failure of mains power, this allows the system to resume operation from where it left off. Also, this avoids the need to repeat the setting-up procedure on successive days of a major OB, when the system may be left set up at the same location.

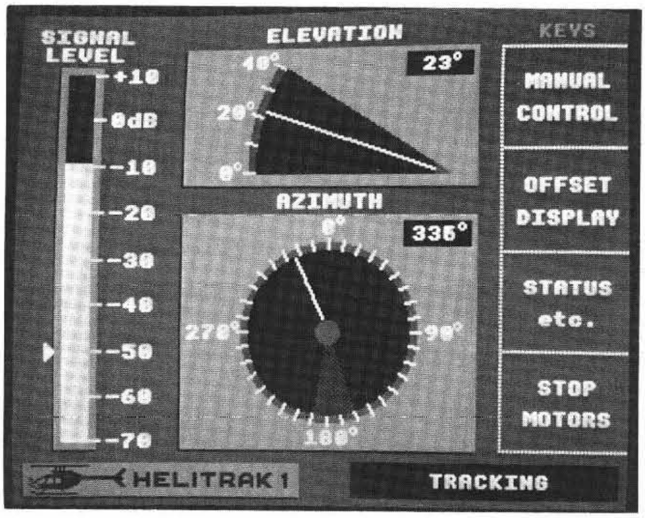

Fig. 16 - The operating display.

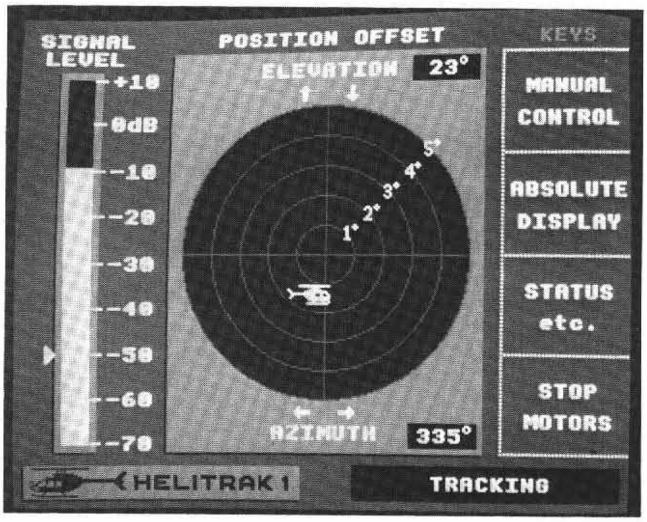

Fig. 17 - The alternative, 'offset' operating display.

6. DEVELOPMENT OF THE COMPONENTS

The development work started with a technical feasibility study, then orders were placed with external firms to supply the specialised components.

6.1 The antenna

The higher-order mode synthesis feed was supplied by ERA Technology Limited; this was possibly the first time such principles had been applied to a prime-focus feed at such a low frequency, with beam scanning in two orthogonal planes. Similar techniques had previously been applied above 10 GHz, mainly to reflector antennas for satellite communications.

A major problem was interaction between the feed and the reflector (i.e. 'back-scatter'). The result was an interference effect which severely limited the bandwidth over which monotonic tracking slopes could be maintained. Useful tracking performance could be maintained in the 2.5 GHz band for only one channel at a time. The feed is shown in Fig. 18 attached to a 1.1 m diameter reflector, and its large size is readily apparent.

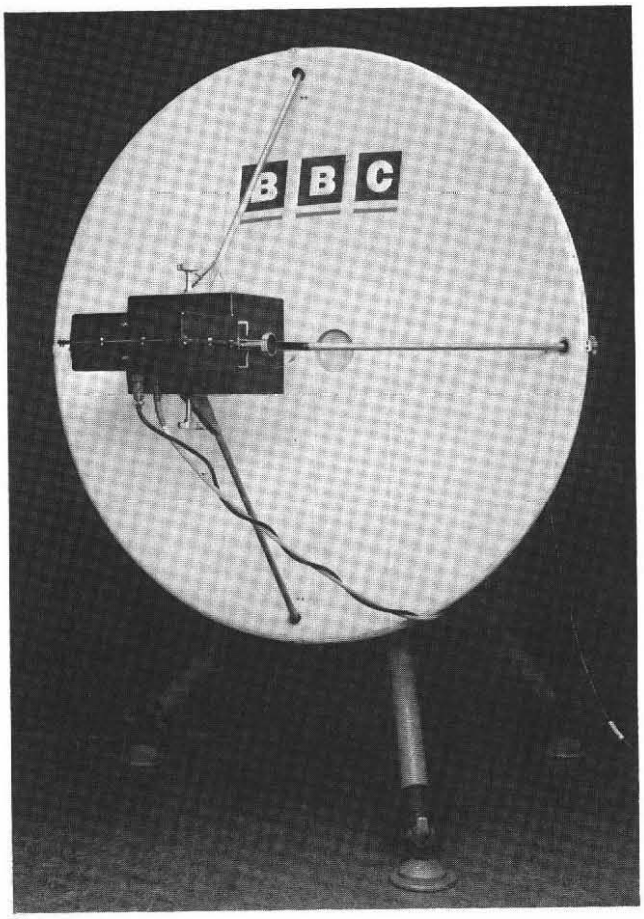

Fig. 18 - The antenna assembly, showing the size of the feed (the reflector has 1.1 m diameter).

The large feed caused a significant degree of aperture blocking, which gave rise to high first-sidelobe levels and reduced the antenna gain below that which is normally achieved with the standard OMT feed. The final antenna gain was about 24 dB, instead of the usual 26 dB (the latter corresponds to 50% aperture efficiency), and the first sidelobes had peak levels as great as −8 dB with respect to the main lobe, instead of the usual−15 dB to −18 dB. The levels of these sidelobes also became unequal when the beam was scanned, but the direction of the asymmetry was frequency-dependent. The expected nulls, between the main lobe and the first sidelobes, were very shallow; at some frequencies the sidelobes merged with the main lobe. These factors all contributed to an ultimate system performance which was inferior to the initial aims, but which, nevertheless, was sufficient to establish the basic principles. Also it was found possible to tune the system to the channel in use by adjustment of the lengths of the feed support struts.

6.2 The receiver

The receiver is essentially of the standard type, with the addition of the 70 MHz 'linear IF' output port.

6.3 The positioner

The positioner, and its associated servo-amplifier, are essentially standard product range items.

A problem which has appeared, concerns the weight of the positioner. Initially, a lower-powered and less heavy version was considered; this version had been replaced in the product range by a more powerful model, the type which was used in this system. This model has a weight of 90 kg (including a wooden transit case), which makes rooftop rigging very difficult.

6.4 The processor

The processor was built at Research Department, using a BBC Master Series 128 micro-computer printed-circuit board (PCB), and a proprietary log. amplifier/detector. All the remaining analogue and digital circuitry, including the sample-and-hold stages, ADCs and DACs, was purpose-built on a number of Eurocard PCBs.

7. OUTSIDE BROADCAST USE OF THE HELITRAK SYSTEM

The cost of hiring a helicopter for testing this system during construction was prohibitive, so, in the early stages of the project, the system was tested using the outdoor radiation-pattern measurement range at Research Department. Tracking in the azimuth plane was tested using a transmitting antenna mounted on a long, horizontal radius arm, attached to the elevated measurement turntable. For tests in the elevation plane, a telescopic mast was used in close proximity to the receiving antenna.

These terrestrial methods were useful initially, but they gave little indication of how the system would perform with a helicopter in flight. Thoughts of equipping a model helicopter were rejected on the grounds of safety and the need to engage a trained operator, so field tests had to be co-ordinated with events for which a transmitting helicopter was in use, and that meant live television OBs.

The system was first tried out at a live OB in March 1989, during the coverage of the University Boat Race, when it was located, along with several manually operated receivers, on the roof of BBC Television Centre. This occasion was halfway through the development period of the feed, and at this stage its tracking performance was poor. Problems were experienced due to a lack of monotonicity in the tracking slopes, and crosstalk between the responses for the two orthogonal control axes. These meant that the antenna was often pointing away from the helicopter by several degrees, so the available gain was not used fully. Also, because of the large sidelobe levels and shallow nulls, the received signals were sometimes subject to a greater degree of multipath distortion than those received by the manually-panned antennas. The latter could be pointed slightly upwards, purposely to minimise multipath reception, by aligning a null with the source of reflected signals.

This live OB provided useful experience, and showed up a number of software 'bugs' as well as the poor antenna performance. A year later, with further development of the feed, the experiment was repeated at Television Centre, for the 1990 Boat Race.

By this time, the antenna's performance had been optimised for the particular channel being used for the 'Helitele' (airborne camera) air-to-ground link. Apart from a few occasions, when multipath distortion was seen on the received pictures, the HELITRAK system provided received signals with greater consistency of S/N ratio than the manually-panned receivers, although, in view of the lower antenna gain, the mean S/N ratio was probably slightly less. Tracking was maintained at all times when the helicopter was airborne and transmitting, and not obscured by a lift-machinery building on the roof. This building was away from the expected flight path, the River Thames, but in the direction of the airfield at Leavesden. The received signals were sent to the network and broadcast live.

Such was the success of this event, that two weeks later the system was used again at Television Centre for the coverage of the Nelson Mandela Concert, held at Wembley Stadium. This time it became the main source of received signals (i.e. the manually-panned receivers acted as the backup to the HELITRAK system, rather than vice versa, as was the case previously).

The next event in 1990, at which it was intended to make major use of helicopters, was the London Marathon; in this case, the system was set up on the roof of a building near London Bridge. However, although the system worked well on the rehearsal day, on the day of the event, the cloud base remained too low (less than 150 m) for the two helicopters to operate, so airborne facilities could not be used.

Later in 1990, the system was used successfully for the coverage of the Formula I Grand Prix, at Silverstone, when, again, it provided the main feed of Helitele signals to the network. On this occasion, the antenna and positioner were mounted on the roof of a radio-link van.

Following this event, the system was handed over to Tel. OBs for normal service use.

7.1 Future improvements

Perhaps the most serious limitation of the system, imposed by the performance of the feed, is its inability to cover all of the channels available for airborne use; ideally, the whole 2.48 - 2.68 GHz band should be covered.

Moreover, noting that multipath problems are sometimes observed on helicopter-to-ground links, circular polarisation may give better performance than linear. However, frequency co-ordination with existing linearly polarised systems will complicate operational planning. In addition, ERA has advised that it is not practical to modify the existing feed to circular polarisation.

It might be worth investigating alternative feed structures to accomplish the same objective, perhaps avoiding the use of waveguide principles in this frequency band.

The rigging problems caused by the weight of the positioner can be reduced by substituting a lighter-weight model, but it is likely that this would offer less mechanical power. Thus, either the maximum available torque or speed would be reduced, and the performance of the system could be compromised. However, the required maximum speed was set by the minimum range and maximum expected air-speed of the helicopter. The maximum required torque (94 Nm), was determined by the wind loading of a 1.1 m dish, inclined to the wind at the least favourable angle, for a maximum operational wind speed of 80 km/hr. Thus, in practice, a smaller and less powerful positioner may give adequate performance under reasonable weather conditions.

If continuous rotation in the azimuth plane were required, a rotary coaxial joint for the RF signal, and numerous slip rings for the connections to the feed and positioner, would be necessary. However, such a mode of operation is exceptional.

8. CONCLUSIONS

'HELITRAK', the new BBC helicopter-tracking receiver system, has three main advantages over existing proprietary 2.5 GHz systems:

(a) It uses many items of existing radio-link equipment which are standardised within the BBC, and does not require a separate tracking receiver.

(b) It uses a new type of tracking feed which requires only one RF connection and can be operated at very high scanning rates. Thus, the system is synchronised to the television field rate to make the tracking function invisible to the viewer. Rapid scanning also makes the tracking system immune to multipath effects caused by the helicopter's rotor blades.

(c) It incorporates a microcomputer which simplifies its setting up and use. This can also apply sophisticated strategies in exceptional circumstances, such as automatic re-acquisition of track using a step track algorithm.

The radio-link receiver, the dish reflector and tripod, the positioner and the servo-amplifier circuitry are all standard products of their respective suppliers; so the only specialised components are the antenna feed, the processor and the software. The principle of using items of standard equipment, wherever possible, simplifies maintenance and saves the expense of purchasing dedicated, non-standard items. This project has demonstrated that this principle can be applied with some success.

Because of limitations in the performance of the antenna, caused mainly by the large physical size of the feed, the performance of the system falls short of what was expected. Nevertheless, the use of the system for live outside broadcasts has shown that an automatically-tracking receiver can offer improved consistency in the quality of the signals received from a transmitting helicopter. It can also lead to increased operational efficiency.

9. ACKNOWLEDGEMENTS

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J.M.C. Scott and the late G. Jay of Television Outside Broadcasts, the end-user department, who provided the incentive for doing this work.

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APPENDIX

Link Budget for a Typical Air-to-ground Link

The performance of a radio link can be judged by the signal-to-noise (S/N) ratio achieved at the end of the link, and the target S/N ratio for most OB links is 46 dB unweighted, or about 57 dB with Unified weighting. This does not mean that a link offering a smaller value of S/N would not be used in practice, especially if it offers a facility unobtainable by other means, which is usually the case when a helicopter is used. Thus, an air-to-ground link providing only 50 dB Unified-weighted S/N ratio might still be considered usable.

The significant parameters of a radio link can be expressed in decibel form in a link budget, giving the ultimate S/N ratio as the result, and then the influence of variables such as the length of the propagation path can be assessed. The following example represents a typical air-to-ground link operating in the 2.5 GHz band. The antennas considered are a Franklin array on the aircraft and a manually-panned 1.1 m dish on the ground. Only ideal, free-space propagation conditions are considered, and the path length is taken as 20 km:

	Transmitter power	5 W	7.0 dBW
+	Transmitting antenna gain		5.0 dBi
−	Free-space propagation loss for 20 km path		−126.4 dB
+	Receiving antenna gain		26.0 dBi
=	Received carrier power		−88.4 dBW
	Receiving antenna noise temperature	290 K	
+	Receiver noise temperature (7 dB NF)	1160 K	
=	Total noise temperature	1450 K	31.6 dBK
+	Effective noise bandwidth	30 MHz	74.8 dBHz [1]
+	Boltzmann constant		−228.6 dBW/Hz/K
=	Received noise power in 30 MHz bandwidth		−122.2 dBW
	Received C/N ratio (in 30 MHz bandwidth)		33.8 dB
+	Relationship between S/N and C/N ratios		15.6 dB [2]
=	Received unweighted S/N ratio		49.4 dB
+	Unified weighting		11.2 dB [3]
=	Received Unified-weighted S/N ratio		60.6 dB

Notes:

[1] The 2.5 GHz band is planned as a number of contiguous channels each 20 MHz wide, but the noise bandwidth of a conventional radio link receiver is about 30 MHz, determined by an IF filter. This is done to provide adequate amplitude and group-delay frequency responses over the 20 MHz channel bandwidth whilst limiting the complexity of the receiver. However, if either of the adjacent channels are in use nearby, as is often the case, an external filter must be interposed between the antenna and the receiver to limit the pass-band width to slightly less than the 20 MHz channel width. This has little impact on the receiver noise temperature because the major noise component arises in the front end, which is downstream of this filter. Also, the resulting S/N ratio is not affected by the reduced RF bandwidth provided that it is greater than the minimum, 'Carson', bandwidth (i.e. twice the baseband-width plus the 'static' peak-to-peak FM deviation), and the C/N ratio exceeds the 11 dB FM threshold. However, any loss introduced by this filter will reduce the received carrier power, and thence the S/N ratio, proportionately.

[2] For 8 MHz FM deviation using CCIR Rec. 405 pre-emphasis for 625-line PAL television signals.

[3] This value is taken from CCIR Rep. 637-1.

The relationship between the path length and the S/N ratio (expressed as a fraction rather than in dB) is an inverse square law; for instance, halving the path length will give four times the fractional S/N ratio (i.e. +6 dB). The value obtained in this example is greater than the target value, and for many actual OBs the path length will often be less than 20 km, so a significant margin may exist. Within this margin, all additional losses, due to multipath propagation, antenna mis-pointing, and extra RF filtering, must be accommodated. Also, when the helicopter is used as a mid-point repeater, a small noise contribution from the ground-to-air link may also need to be considered.

For the maximum required range of 80 km, in ideal conditions the target S/N would be achieved if the transmitter power was increased by 8.4 dB to 35 W. In practice, with power amplifiers available providing only up to 25 W, inevitably some reduction in the maximum S/N is accepted. However, with 25 W transmitter power (7 dB greater than 5 W) and 80 km range (giving 12 dB greater propagation loss than a 20 km path), the received C/N ratio is reduced to 28.8 dB which is well above the 11 dB FM threshold. In this case the Unified-weighted S/N ratio would be 55.6 dB.

Using the HELITRAK system instead of the manually-panned receiving antenna, the resulting C/N and S/N ratios will be 2 dB smaller on account of the reduced antenna gain.

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